The results of tests with the reduced-bandwidth interferer are presented in the next section followed by detailed results of the tests described above.

1-MHZ BANDWIDTH UNDESIRED SIGNAL

Most tests performed for this report involved undesired signals that filled, or nearly filled, a 6-MHz wide TV channel. Interference rejection tests were also performed on one DTV receiver (receiver N1) using a reduced-bandwidth source to determine the effect of a narrower undesired signal spectrum. Specifically, a Gaussian noise signal with a 1-MHz 3-dB width was created using the same vector signal generator that was used to generate 5.38-MHz wide Gaussian noise signal. Spectral plots were shown in Figures 2-1 and 2-2.

The interference rejection measurements were performed with the 1-MHz bandwidth undesired signal centered on each channel from N-16 to N+16, except for channel N. In addition, where the 8-VSB-width source had identified interference vulnerabilities, tests were performed with the 1-MHz wide source stepped in 1-MHz or 2-MHz steps to look for finer frequency dependence of the vulnerability. The desired signal was set to -68 dBm.

Figure 7-1 shows the threshold D/U ratio measurements for the 1-MHz wide Gaussian noise source along with the results (from Chapter 5) for the 5.38-MHz-wide baseline source. (The baseline source was a Gaussian noise source bandlimited to match the 3-dB width of an 8-VSB signal, except that for N-1 and N+1, an actual 8-VSB source was used in order to achieve band-edge characteristics adequate for adjacent channel testing.) Though measurements were made from N-16 to N+16, the plot is limited to a range over which the 1-MHz width tests yielded D/U ratios that were above the measurement limit; consequently, the plot extends from channel N-9 through the center point of channel N+16. Vertical gridlines correspond to the boundaries between TV channels.

N+7 Interference

In general the two plots in Figure 7-1 track each other reasonably well except where narrowband vulnerabilities are apparent. One point of interest is the interference susceptibility peak at N+7. The 1-MHz data shows high susceptibility when the undesired signal is centered at 44 MHz, but no measurable interference susceptibility at 43 or 45 MHz (or elsewhere within channel N+7). Based on the bandwidth ratio of the two signal sources (5.38 MHz / 1 MHz), one would expect the 1-MHz wide signal to have a 7.3 dB greater power spectral density than the 5.38 MHz wide signal used for the baseline tests when the power levels are the same. This closely matches the 6.7 dB difference in D/U peaks in N+7 for the two signal bandwidths.

It appears that N+7 interference is seen only when the undesired signal overlaps the receiver's local-oscillator frequency, 44 MHz above the center of the channel to which the DTV receiver is tuned. Our initial hypothesis for the cause of the N+7 peak in the previous D/U plots was that the undesired signal was acting as a noise-like local oscillator—beating with the desired signal and creating a mixer product that falls within the IF frequency of the TV. Such a mechanism would not result in the narrow sensitivity spike observed here. Rather, the interference mechanism apparently involves interaction between the DTV receiver's local oscillator and the incoming undesired signal when the spectrum of the incoming signal overlaps the local oscillator frequency.

DESIRED SIGNAL SOURCE: SFU VERSUS ATSC997

Test results described in Chapter 5, in the section entitled "Effect of Desired Signal Source", demonstrate that, with no undesired signals present, DTV receivers could operate at a lower desired signal level when the desired signal was supplied by a newer, higher-quality 8-VSB signal source (the Rohde and Schwarz

SFU acquired by the FCC late in this measurement program) than when it was supplied by the Sencore ATSC997, the source that supplied the desired signal for most of the measurements presented in this report (and the only 8-VSB signal source available at the Laboratory during most of the channel-30 test period). That section of Chapter 5 also presents the results of signal quality tests, such as modulation error ratio, on each of the two sources.

The tests presented here look at the effect of the desired signal source on susceptibility to interference. Specifically, interference rejection measurements were performed with a desired signal level of -68 dBm on channel 30 supplied by each of the two signal generators.

Table 7-2 shows the D/U ratios measured with the SFU as the desired signal source relative to the baseline measurements made with the ATSC997 as the source. The table also includes means and standard deviations calculated across channel offsets (statistics computed on five measurements) for each DTV receiver, across DTV receivers except for receiver G5 (statistics computed on seven measurements), and across both the channel offsets and receivers (statistics computed on 35 measurements).

Table 7-2. D/U Ratio With SFU as Desired Signal Source Relative to That With Baseline Generator (ATSC997)

Channel Offset	D/U Ratio Relative to Baseline (dB)								Mean (dB) (Excluding G4)	Standard Deviation (dB) (Excluding G4)
	A3	D3	I1	J1	M1	N1	O1	G4		
N-6	-1.37	-0.01	-1.54	-1.42	-1.39	-1.96	-1.29	-6.29	***-1.28***	***0.60***
N-4	-1.15	-0.11	-1.00	-1.44	-1.16	-1.51	-1.03	-5.16	***-1.06***	***0.46***
N-3	-1.03	-0.88	-0.98	-0.57	-1.10	-1.50	-1.06	-5.70	***-1.02***	***0.28***
N-2	-1.21	-0.56	-0.96	-1.63	-1.14	-1.42	-0.90	-4.82	***-1.12***	***0.35***
N+2	-1.28	-1.50	-1.27	-1.44	-0.75	-1.30	-1.12	-4.49	***-1.24***	***0.25***
Mean	***-1.21***	***-0.61***	***-1.15***	***-1.30***	***-1.11***	***-1.54***	***-1.08***	***-5.29***	***-1.14***	
Std Dev	***0.13***	***0.61***	***0.25***	***0.42***	***0.23***	***0.25***	***0.14***	***0.72***		***0.40***

Note:
The overall means and standard deviations (lower right corner of the chart) omitted data for receiver G4 for reasons discussed in the text.

Overall, the SFU measurements differed from the baseline measurements by an average of about -1.1 dB (excluding receiver G4), indicating that the receivers were slightly less susceptible to out-of-channel interference when looking at a desired signal from the SFU as opposed to the ATSC997. This difference reduces to -1.0 dB if the newer "repeat baseline" mean is subtracted. A difference of 1 dB in an individual measurement having a 0.4 dB standard deviation is large enough to suggest a statistically significant difference. If the measurement differences were deemed independent of one another, the standard deviation of the mean would be reduced by a factor of square-root of 35 (*i.e.*, 5.9) to less than 0.1 dB. The size of the 1-dB mean difference relative to this computed standard deviation provides strong evidence that this is a real difference rather than a statistical artifact. Other measurements, presented in Chapter 5, support the notion that there is a real difference between the signal sources that influences the performance of DTV receivers.

Except for the tests with receiver G4, there appears to be no major trend across the receivers or the channel offsets.

The measurements for receiver G4 were dramatically different from those for the other receivers. The change in signal sources *appeared* to have a 5 dB effect on D/U ratios for that receiver; however, when the "repeat baseline tests" were performed (the next section of this chapter), the measurements on receiver G4 were performed twice with results differing by as much as 6 dB for one of the channel offsets. Furthermore, when receiver threshold without interference (D_{MIN}) had been measured as part of the D_{MIN}+3 dB measurements presented in Chapter 5, D_{MIN} measurements on consecutive days yielded results differing by 5.4 dB. Later, in measuring intermodulation effects with pairs of undesired signals of unequal power, another discrepancy of about 6 dB arose for that receiver. No other receiver exhibited such variations. Although receiver G4 is the best-performing receiver tested (in terms of interference rejection capabilities), there appears to be something intermittent or variable in its performance. Consequently, results for G4 were omitted from the overall mean and standard deviation data presented in this chapter.

The results suggest that degraded signal quality from the ATSC997 reduces the receiver's available margin to handle interference. Signal quality measurements presented in Chapter 5 did show that the signal from the ATSC997 is inferior to that from the ATSC997, but we are unable to identify a signal quality measurement low enough to explain the performance differences of the TV receivers.

REPEAT BASELINE TEST

We wanted to determine whether the 1-dB change in D/U ratio discussed in the previous section was actually related to the change in signal sources or whether it might have been caused by some aspect of the test setup. A different spectrum analyzer was used for the comparative tests than for the baseline tests. Also, the baseline tests had been performed about four months earlier than the comparative tests, so it was plausible that some other unintended change in the equipment setup or performance might have contributed to the observed change.

To rule out such equipment and test-setup issues the baseline tests were repeated. Table 7-3 shows the results. The repeat test produced results that, on average, differed from the original measurements by only about 0.1 dB. The standard deviation of those differences was 0.33 dB. This agreement between the four-month old baseline data and new measurements is considered quite good.

Table 7-3. D/U Ratio for Repeat of Baseline Test Relative to Baseline

Channel Offset	D/U Ratio Relative to Baseline (dB)									Mean (dB) (Excluding G4)	Standard Deviation (dB) (Excluding G4)
	A3	**D3**	**I1**	**J1**	**M1**	**N1**	**O1**	**G4**	*G4 again*		
N-6	-0.73	0.01	0.00	0.02	-0.48	-0.27	-0.11	-6.23	*-0.23*	**-0.22**	**0.29**
N-4	-0.69	0.11	0.50	0.13	-0.36	-0.22	-0.01	-3.37	*-0.09*	**-0.08**	**0.39**
N-3	-0.47	-0.68	0.15	0.06	-0.26	-0.44	0.10	0.14	*0.63*	**-0.22**	**0.33**
N-2	-0.31	-0.21	0.33	0.00	-0.04	-0.15	0.12	0.68	*0.19*	**-0.04**	**0.22**
N+2	0.06	-0.90	-0.03	0.15	0.44	-0.01	0.13	-0.28	*0.36*	**-0.02**	**0.42**
Mean	***-0.43***	***-0.33***	***0.19***	***0.07***	***-0.14***	***-0.22***	***0.05***	***-1.81***	***0.17***	**-0.12**	
Std Dev	***0.32***	***0.44***	***0.22***	***0.07***	***0.36***	***0.16***	***0.10***	***2.93***	***0.34***		**0.33**

Note:
The overall means and standard deviations (lower right corner of the chart) omitted data for receiver G4 for reasons discussed in the section of this chapter entitled, "Desired Signal Source: SFU Versus ATSC997".

Results for receiver G4 were omitted from the statistics presented in the previous paragraph for reasons described in the previous section. The measurements shown in the "G4" column were made on a Friday. G4 was measured again ("G4 again" column) on the following Monday with significantly different results.

UNDESIRED SIGNAL TYPE: 8-VSB VERSUS BANDLIMITED GAUSSIAN NOISE

Table 7-4 shows the effect of using an 8-VSB signal instead of bandlimited white Gaussian noise as the *undesired* signal. On average, the TVs are 1.3 dB less susceptible to interference from a DTV 8-VSB signal than from white Gaussian noise bandlimited to the same 3-dB bandwidth. The difference reduces to 1.2 dB when the newer baseline measurements are used as the reference. Given that the standard deviation of the mean is expected to be much less than the 0.68 dB value for individual measurements (by a factor of 5.9, if individual differences were statistically independent), the observed difference appears to be real, rather than a statistical artifact.

The reason for the difference could be related to the amplitude statistics of the respective waveforms. An 8-VSB waveform is likely to exhibit fewer and smaller amplitude extremes (*i.e.*, less time spent at levels far above the average power) than a Gaussian noise signal. For linear interference mechanisms, the interference signal (within the TV) is linearly related to the incoming undesired signal, and the interference power (within the TV) is related to the mean-square of that signal (*i.e.*, the second-order moment). For a third-order interference mechanism on the other hand, the interference signal in the TV is related to the cube of the incoming undesired signal, and the interference power in the TV is related to the 6^{th}-order moment of the undesired signal. We consider it likely that the high order moments of an 8-VSB signal are lower than those for a Gaussian noise signal (or for an OFDM signal) of the same power.

Table 7-4. D/U Ratio With 8-VSB as Undesired Signal Relative to That with Bandlimited Gaussian Noise

Channel Offset	D/U Ratio Relative to Baseline (dB)								Mean (dB) (Excluding G4)	Standard Deviation (dB) (Excluding G4)
	A3	D3	I1	J1	M1	N1	O1	G4		
N-6	-1.32	-1.25	-1.61	-0.73	-1.85	-0.87	-1.76	-3.72	**-1.34**	**0.43**
N-4	-1.31	-1.43	-0.92	-1.07	-1.66	-1.07	-0.87	-1.94	**-1.19**	**0.29**
N-3	-0.79	-1.85	-2.23	-1.73	-1.50	-2.38	-1.47	-0.26	**-1.71**	**0.53**
N-2	-0.76	-1.94	-2.31	-0.53	-1.31	-0.91	-0.71	-0.89	**-1.21**	**0.68**
N+2	0.02	-2.99	-1.94	-0.48	-0.04	-0.67	-0.40	0.50	**-0.93**	**1.12**
Mean	***-0.83***	***-1.89***	***-1.80***	***-0.91***	***-1.27***	***-1.18***	***-1.04***	***-1.26***	**-1.28**	
Std Dev	***0.55***	***0.68***	***0.56***	***0.51***	***0.72***	***0.69***	***0.56***	***1.64***		**0.68**

Note:
The overall means and standard deviations (lower right corner of the chart) omitted data for receiver G4 for reasons discussed in the section of this chapter entitled, "Desired Signal Source: SFU Versus ATSC997".

The variability among these measured differences in D/U ratios for the change in undesired signal type is somewhat larger than that associated with the change in the desired signal source. There may be patterns in the data. For example, the undesired signal type appears to have a greater effect at N-3 than at N+2. Whether these differences are associated with the order of the associated interference mechanisms-in conjunction with moments of the undesired signals (as discussed in the previous paragraph) is uncertain because the order of the interference mechanisms is often masked by AGC operation—a topic to be addressed in subsequent chapters.

UNDESIRED SIGNAL TYPE: DVB-H OFDM VERSUS BANDLIMITED GAUSSIAN NOISE

Tests were performed with an OFDM undesired signal and compared to the tests with bandlimited Gaussian noise. The OFDM signal was produced by an Agilent E4438C vector signal generator using Agilent Signal Studio for DVB software. The signal type was selected as DVB-H, an OFDM signal format designed for mobile video application. The waveform parameters were as follows:

- Size 2k
- Modulation 64 QAM
- Channel width 5 MHz
- Guard interval 1/8

Plots of the signal spectrum were shown in Figures 2-1 and 2-2. The bandwidth measurements were shown in Table 2-1.

Table 7-5 shows the D/U ratio measurements made with the DVB-H source as the undesired signal relative to those for the bandlimited Gaussian noise baseline. The table includes one point that is greatly inconsistent with the others (by about 5 dB). That measurement, for receiver N1 with the undesired signal on channel N-3, indicates that the receiver was significantly less susceptible to the DVB-H interference than to the bandlimited Gaussian noise signal.

Table 7-5. D/U Ratio With DVB-H as Undesired Signal Relative to That with Bandlimited Gaussian Noise

Channel Offset	D/U Ratio Relative to Baseline (dB)								Mean (dB) (Excluding G4)	Standard Deviation (dB) (Excluding G4)
	A3	D3	I1	J1	M1	N1	O1	G4		
N-6	-0.87	-0.08	0.24	0.17	-0.78	-0.23	-0.54	-1.47	**-0.30**	**0.44**
N-4	-0.94	-0.1	1.92	0.04	-0.74	-0.43	-0.54	-0.87	**-0.11**	**0.96**
N-3	-0.53	-0.53	0.09	-1.13	-0.52	***-5.44***	-0.53	0.49	**-1.23**	**1.89**
N-2	-0.54	-0.15	0.2	-0.09	-0.05	-0.08	0.00	-0.08	**-0.10**	**0.22**
N+2	0.12	-2.37	-0.57	0.26	0.43	0.11	0.24	-1.53	**-0.25**	**0.99**
Mean	***-0.55***	***-0.65***	***0.38***	***-0.15***	***-0.33***	***-1.21***	***-0.27***	***-0.69***	**-0.40 (-0.25)**	
Std Dev	***0.42***	***0.98***	***0.92***	***0.56***	***0.52***	**2.37**	***0.37***	***0.88***		**1.09 (0.66)**

Note:
The overall means and standard deviations (lower right corner of the chart) exclude data for receiver G4 for reasons discussed in the section of this chapter entitled, "Desired Signal Source: SFU Versus ATSC997". The means and standard deviations shown in parentheses also exclude the value associated with receiver N1 at N-3 ***boxed bold italics*** *for reasons discussed below.*

Since the 4.8 MHz width of the DVB-H waveform, combined with its extremely steep spectrum rolloff on each side, left a gap of about 0.6 MHz between each side of the waveform's spectrum and the channel edges, we wondered whether receiver N1 might have a narrowband interference susceptibility within channel N-4 that falls outside of the DVB-H waveform bandwidth. To test this theory, the measurement was repeated twice, once with the waveform shifted 0.5 MHz downward and once with the waveform shifted 0.5 MHz upward. The measured D/U ratios relative to the baseline were as follows:

- Frequency shift = -0.5 MHz   D/U relative to baseline = -5.97 dB
- Frequency shift = +0.5 MHz   D/U relative to baseline = +1.95 dB

The results suggest that this receiver had a narrowband susceptibility between the upper edge of the DVB-H waveform, when it was centered on the channel, and the upper edge of the channel. The tests conducted with a 1-MHz wide interferer (Figure 7-1) happen to have been performed with the same receiver. Those tests do reveal a rapidly increasing susceptibility to interference as the undesired signal approaches the upper band edge for channel N-3.

The mean and standard deviation shown in the table were computed in the same manner those for the other comparison tests in this chapter. In addition, a second computation was performed omitting the measurement associated with N-4 for receiver N1 because the reduced width of the OFDM signal had apparently caused a narrowband susceptibility to be missed.

Except for the one aberrant point caused by placement of the DVB-H waveform spectrum, there is no obvious trend in the data.

Using the parenthetical value of mean from the table (-0.25 dB) and subtracting the mean for the "repeat baseline" test shows a mean difference of -0.1 dB between the OFDM results and the Gaussian results. The interference effect of the DVB-H waveform appears to be essentially identical to that of bandlimited Gaussian noise.

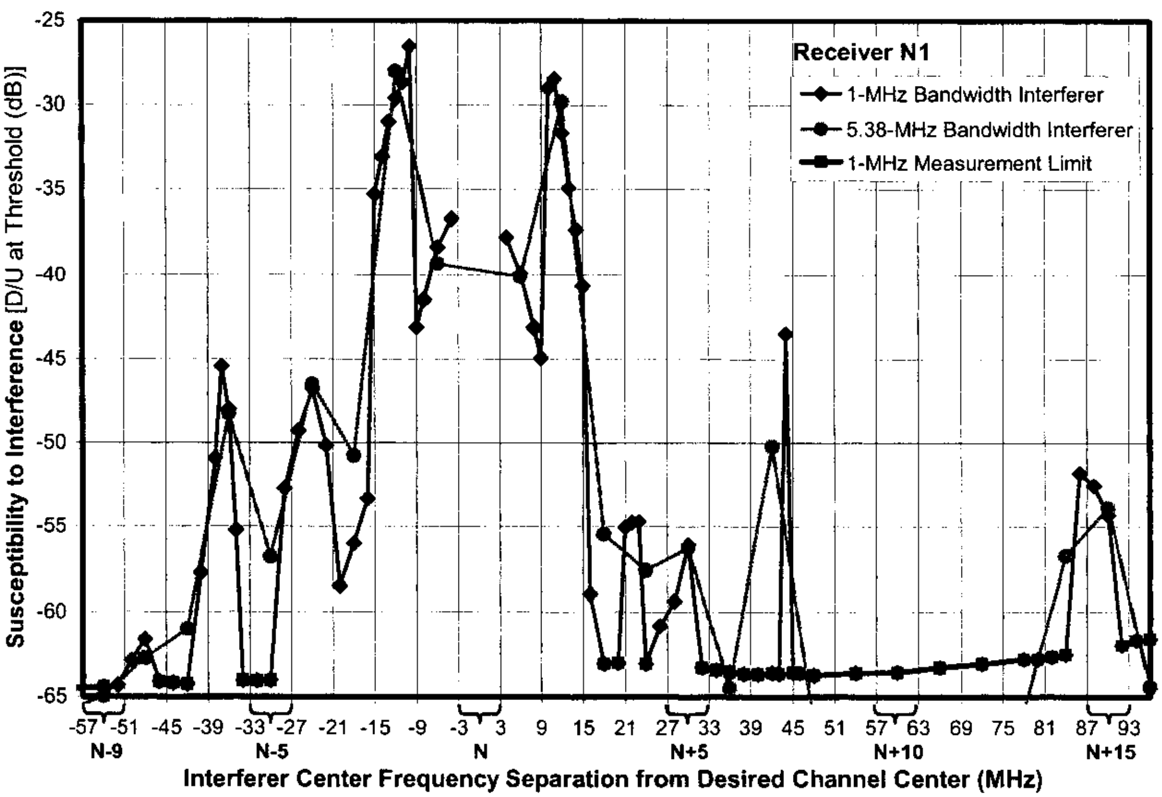

Figure 7-1. D/U With 1-MHz Undesired Signal Bandwidth

CHAPTER 8
THEORETICAL FRAMEWORK FOR OUT-OF-CHANNEL INTERFERENCE

Before presenting more measurement results, we devote a chapter to establishing a theoretical framework that will be used for interpreting or extending the measurement results in most of the remaining chapters. We apply this theoretical basis to some of the common interference mechanisms that apply to TV reception. A more detailed derivation is included in Appendix B.

When a DTV receiver operates in the presence of white Gaussian *co-channel* interference, the threshold of visibility (TOV) of picture degradation occurs when the desired signal power D exceeds the co-channel interference by about 15 dB.* This number may vary somewhat for noise having other statistical properties, and may be much lower if the noise is heavily concentrated at a band edge where filtering in the DTV provides additional rejection; nonetheless, one expects that, as signal power D varies, the undesired signal power at threshold will vary linearly with it—resulting a constant D/U ratio as D or U are varied. This relationship holds whenever the co-channel interference is high enough that the effect of internal noise in the receiver becomes insignificant.

For most *out-of-channel* interference mechanisms, the DTV receiver unintentionally converts a small portion of the out-of-channel power into co-channel power. If one knows the amount of conversion into co-channel interference, one can treat the problem as a co-channel interference problem, which is relatively well understood, as described above. In this formulation of the problem, measuring the desired signal power D at the TOV provides an indirect method of measuring the co-channel power created internal to the receiver, since we know that the co-channel power will be about 15 dB below the measured value of D.

The conversion process by the DTV receiver from out-of-channel interference to co-channel interference may be linear or nonlinear. If it is linear, then the internally-created co-channel interference will vary linearly with the out-of-channel interference power U causing the value of the desired signal power D at threshold to vary linearly with U. The result will be that threshold D/U ratio will be constant as D or U is varied. If the conversion process is nonlinear, then the relationship between D and U will be nonlinear and the D/U ratio will vary with D and U.

INTERFERENCE MECHANISMS AND ORDER

We will assume that the *co-channel* interference power created by the DTV receiver in response to an *out-of-channel* undesired signal power U will be proportional to $D^L U^M$, where L and M are integer constants that define the ***order*** of the interference mechanism. For most interference mechanisms, L will be zero, so only the U^M term exists. The following are among the interference mechanisms that can be modeled by this formulation.

- Linear interference: L=0, M=1. Creates co-channel interference proportional to U.
  - ◊ Example: mixer image. The mixer in a TV receiver converts the spectrum of the intended channel of the received signal to an intermediate frequency (IF) where it can be filtered more precisely to pass the desired channel while rejecting the undesired frequencies. Unfortunately, in single-conversion tuners a second a 6-MHz wide portion of the input spectrum centered 88 MHz above the desired channel is also converted to that same IF. Filtering prior to the mixer strongly diminishes—but doesn't fully extinguish—this unintended signal.

* The SHVERA Study test results on 28 receivers showed that D must exceed U by amounts ranging from 14.9 to 15.8 dB, with a median value of 15.3 dB.

- ◊ Example: leakage of the adjacent channel signal through the channel selection filter of the DTV receiver would also constitute a linear interference mechanism.
- Second-order interference: L=0, M=2. Creates co-channel interference proportional to U^2.
  - ◊ Example: "half-IF" taboo. The second harmonic of an undesired signal 22 MHz above the desired signal beats with the second harmonic of the receiver's local oscillator, creating a *difference frequency that falls within the IF band of the receiver.*
- Third-order interference: L=0, M=3. Creates co-channel interference proportional to U^3.
  - ◊ Example: third-order intermodulation (IM3) of a single, adjacent-channel undesired signal. IM3 creates spectral components that spill into each adjacent channel.
  - ◊ Example: third-order intermodulation (IM3) of a pair of undesired channels placed at channels N+K and N+2K where N is the desired channel. In this case, the interference power created in channel N is proportional to $U_{N+K}^2 U_{N+2K}$. The result is a process that is second-order in terms of U_{N+K} and linear in terms of U_{N+2K}; however, if the two undesired signals are set to equal powers and varied in amplitude together, the resulting interference is third order.
- Cross-modulation: L=1, M=2. Creates co-channel interference proportional to DU^2.
  - ◊ Cross-modulation is essentially a third-order effect, but the co-channel interference created is proportional to D and to U^2. As a result, increasing the desired signal power does not improve the signal-to-interference ratio.

THRESHOLD OF VISIBILITY OF PICTURE DEGRADATION DUE TO INTERFERENCE

As stated earlier, the TOV for a DTV receiver occurs when the ratio of the desired signal to the co-channel interference-plus-noise exceeds the required signal-to-noise ratio $\mathbf{SNR_R}$ for the DTV receiver. We will assume that the co-channel interference-plus-noise power includes two components: receiver noise power $\mathbf{N_R}$ and the co-channel interference that was created by linear or nonlinear interference mechanisms operating on the out-of-channel undesired signal ($\mathbf{c\ D^L U^M}$, where **c** is a constant). Note that the both the co-channel receiver noise and the co-channel interference power are generated *within* the DTV receiver. The levels we refer to here are expressed in terms of equivalent *input* power levels to the TV.

Thus we can say

$$D / (c\, D^L U^M + N_R) = SNR_R$$

For 8-VSB DTV receivers the SNR_R is about 33.9 (*i.e.*, 15.3 dB converted to a linear power ratio) if the noise and interference have white spectra and Gaussian statistics. Note that, while the receiver noise is likely to be white and Gaussian, the interference may not be—in which case a different SNR would apply to it, but we will neglect that difference for the discussion here.

We note that the threshold desired signal power in the absence of interference (D_{MIN}) is given by

$$D_{MIN} = SNR_R\, N_R$$

Thus we can write,

$$D = SNR_R\, c\, D^L U^M + D_{MIN}$$

SLOPES OF LOG-LOG PLOTS OF D, U, AND D/U

We first consider the case in which the desired signal at threshold is much larger than D_{MIN}. We can then write,

$$D \approx SNR_R \, c \, D^L U^M$$

Depending on the values of L and M, a plot of D versus U (in power units, such as microwatts) may be linear or nonlinear; however, a plot of log(D) versus log(U) will always be linear. Thus, plots of D versus U in units of dBm will be straight lines, since decibels are a logarithmic unit. The slope of such a log-log plot indicates the order of the interference mechanism. For example, for a third-order interference mechanism (L=0, M=3), the slope of log-D versus log-U will be 3 dB/dB and the log-U versus log-D will be 0.333 dB/dB; similarly, a plot of D/U versus D on a log-log scale will have a slope of 0.667 dB/dB. The expected slopes of log-log plots for various interference mechanisms are summarized in Table 8-1. The final row of the table will be explained in the next section.

Table 8-1. Slopes of Log-Log Plots of D, U, and D/U for Various Interference Mechanisms

Interference Mechanism	Slope of Log (D) Versus Log (U) in dB/dB	Slope of Log (U) Versus Log (D) in dB/dB	Slope of Log (D/U) Versus Log (D) in dB/dB	Characterization
Linear (M = 1)	1	1	0	Constant D/U
Second order (M = 2)	2	0.5	0.5	
Third order (including third-order intermodulation of a pair of equal-power interferers) (M = 3)	3	0.333	0.667	
Cross modulation (M = 2, L = 1)	Infinite	0	1	Constant U
AGC-Stabilized Nonlinear[1]	1	1	0	Constant D/U

Notes:
[1] *See next section ("Effect of AGC")*

EFFECT OF AGC

Television receivers incorporate an automatic gain control (AGC) function that adjusts the gain of one or more stages in the tuner in order to maintain acceptable signal levels. The gain may be constant (at its maximum) when signal levels are low. As signal levels rise, a point is reached at which the AGC begins to reduce the gain to avoid overdriving the tuner circuitry. The AGC control function may be based on the level of the desired signal, or on the combined power of the desired and undesired signals at some point in the tuner (typically the mixer), or both.[*] Typically, the AGC will act to reduce the gain of both RF and IF amplifier stages, but not necessarily at the same signal levels. As input signal levels increase, the AGC may act to reduce IF gain first—waiting for higher signal levels before reducing RF amplifier gain (delayed AGC).

If we consider an interference mechanism that is caused by a nonlinearity at a given point in the tuner, the expected nonlinear behavior described in the previous section will exist only for signal levels up to the point at which AGC begins to reduce gain *prior to the point of the nonlinearity*. For example, if a given

[*] O. Bendov and C. B. Patel, "Television Receiver Optimization in the Presence of Adjacent Channel Interference", IEEE Transactions On Broadcasting, Vol. 51, No. 1, March 2005, p.38-39.

interference mechanism is caused by nonlinearity in the receiver's mixer, AGC gain reductions in the IF amplifier will not affect it, but gain reductions in the RF amplifier will.

Under the assumption that AGC operation tends to adjust gain so as to maintain either the desired signal or the undesired signal at a constant level* at the point of nonlinearity, then the interference begins to behave as if it were linear (with the possible exception of cross-modulation when AGC operates on undesired signal power).† That is, further increases in D result in corresponding increases in threshold U, so D/U remains constant. This occurs because the amplitudes at the nonlinearity remain constant in spite of further increases in input signal levels at the receiver's antenna input terminal. The results are derived in Appendix B.

This suggests that we may see interference that behaves like third-order interference, for example, at low signal levels, but switches to linear behavior when a certain signal threshold associated with the AGC is exceeded. The last row of Table 8-1 refers this effect.

WEAK SIGNALS

As stated above, both the linear and the nonlinear interference mechanisms will plot as straight lines on a log-log plot (*e.g.*, plotting U, D, and D/U in decibels). However, this relationship is true only at desired input signal levels high enough to make the receiver's own internal noise an insignificant contributor to performance.

As signal level approaches the threshold for the receiver in absence of interference, the receiver becomes increasingly more susceptible to interference than such straight-line projections would predict.

Referring to the earlier equation defining the interference threshold, we had

$$D = SNR_R \, c \, D^L U^M + D_{MIN}$$

The presence of the quantity D_{MIN} causes the log-log plots to deviate from straight-line behavior as D approaches D_{MIN}. Figures 8-1 through 8-4 depict the deviation of threshold U versus D from a straight line on a log-log plot for linear, second-order, third-order, and cross-modulation interference, respectively. It can be seen that for the first three cases, the distance in the D direction from the straight line projection is 3 dB and 6.9 dB when $D = D_{MIN} + 3$ dB and $D_{MIN} + 1$ dB, respectively. Distances in the U direction vary with slope of the line as shown in the illustrations and in Table 8-2. Thus, for example, when desired signal level drops to a point 1 dB above the receiver's threshold (D_{MIN}), the DTV receiver

* AGC will generally act on the basis of either desired signal power or total power at a point in the tuner. Broadband AGC is an example of the latter. If operating on the basis of total power, the relative contributions of the desired and undesired signals at the AGC control point may differ from their relative levels at the receiver input due to filtering within the receiver. In the case of AGC operation based on total power, the two bounding cases—desired signal being dominant and undesired signal being dominant—were considered in the analysis.

† For the case in which the AGC acts to maintain the *desired* signal at a constant power at the point of tuner nonlinearity that is responsible for the dominant interference, Appendix B shows the math behind the transition to linear behavior for each of the four types of interference discussed in this chapter. For the case in which the AGC acts to maintain the *undesired* signal at a constant level, Appendix B shows the math only for three of the four interference categories. The case of cross-modulation with AGC acting on undesired signal was not completely solved. When desired signal power is much greater than D_{MIN}, cross-modulation causes TOV to occur at a fixed threshold undesired signal power (U), independent of the desired signal power, for cases in which gain is constant. If the undesired signal rises to a point at which the AGC begins reducing gain prior to the point of nonlinearity, the model suggests the following: (1) if that AGC threshold occurs *before* the TOV is reached, then the subsequent gain reductions will prevent TOV from being reached as U increases further (until the range of gain reduction for the AGC is exceeded or another nonlinearity becomes significant); (2) if the AGC threshold occurs *after* TOV is reached, then the TV will remain in a degraded picture state with further increases in undesired signal power.

will be sensitive to interference from undesired signals that are lower than a straight-line projection would predict, by amounts ranging from 2.3 to 6.9 dB, depending on the order of the interference mechanism.

In terms of deviation from the straight-line projection, the effect of AGC varies according to whether the AGC is driven primarily by desired signal power or by undesired signal power. In the former case, the deviation from a straight-line projection matches that of the underlying interference mechanism. In the latter, the deviation matches that of a linear process.

Table 8-2. Deviation in Threshold U from Straight-Line Projection as D approaches D_{MIN}

Interference Mechanism	Deviation in Threshold U from Straight-Line Projection (dB)			
	D/D_{MIN}[1] = 16 dBm	D/D_{MIN} = 3 dB	D/D_{MIN} = 1 dB	D/D_{MIN} = 0 dB
Linear (M = 1)	-0.1	-3.0	-6.9	Infinite
Second order (M = 2)		-1.5	-3.4	Infinite
Third order (including third-order intermodulation of a pair of equal-power interferers) (M = 3)		-1.0	-2.3	Infinite
Cross modulation (M = 2, L = 1)		-1.5	-3.4	Infinite
AGC-Stabilized Nonlinear w/U driving AGC[2]	-0.1	-3.0	-6.9	Infinite

Note:
[1] For the nominal D_{MIN} value of -84 dBm, D/D_{MIN} = 16 dB when D = -68 dBm
[2] With desired signal driving AGC, deviation from straight-line projection matches that of the original nonlinear process, except in the case of cross-modulation, which was not completely solved.

IM3 WITH PAIRED SIGNALS

When the interference is caused by a pair of signals located at channels N+K and N+2K, the receiver creates third-order intermodulation (IM3) products in the desired channel N.

In this case, Appendix B shows that the interference equation becomes:

$D = (SNR_R / IP3^2)\, U_{N+K}^2 U_{N+2K} + D_{MIN}$.

We will use the term $IP3 / SNR_R^{1/2}$ to quantify the IM3 properties of the receiver by computing it from measurements of D and U at threshold with $D >> D_{MIN}$ and $U = U_{N+K} = U_{N+2K}$.

$IP3 / SNR_R^{1/2} = (U^3 / D)^{1/2}$

or, in decibel units

$(IP3 / SNR_R^{1/2})|_{dB} = 1.5\, U|_{dB} - 0.5\, D|_{dB}$

where $|_{dB}$ means conversion to decibels:

$X|_{dB} = 10 \log(X)$

To compute interference susceptibilities knowing $(IP3 / SNR_R^{1/2})|_{dB}$, we will use the following.

$U_{N+K}|_{dB} = (IP3 / SNR_R^{1/2})|_{dB} + (D|_{dB} - U_{N+2K}|_{dB})/2$

or,

$U_{N+2K}|_{dB} = 2(IP3 / SNR_R^{1/2})|_{dB} + D|_{dB} - 2\ U_{N+K}|_{dB}]$

See Appendix B for details the derivation.

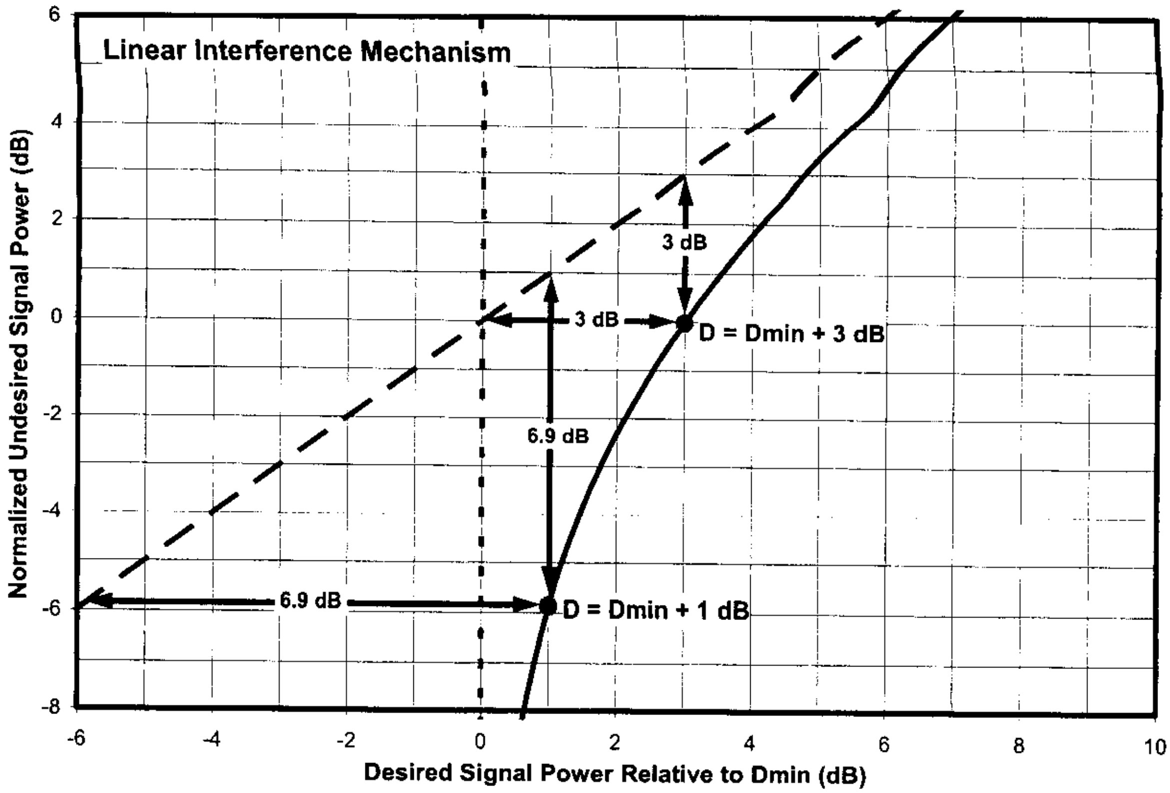

Figure 8-1. Deviation of Log-U Versus Log-D From Straight Line For Linear Interference

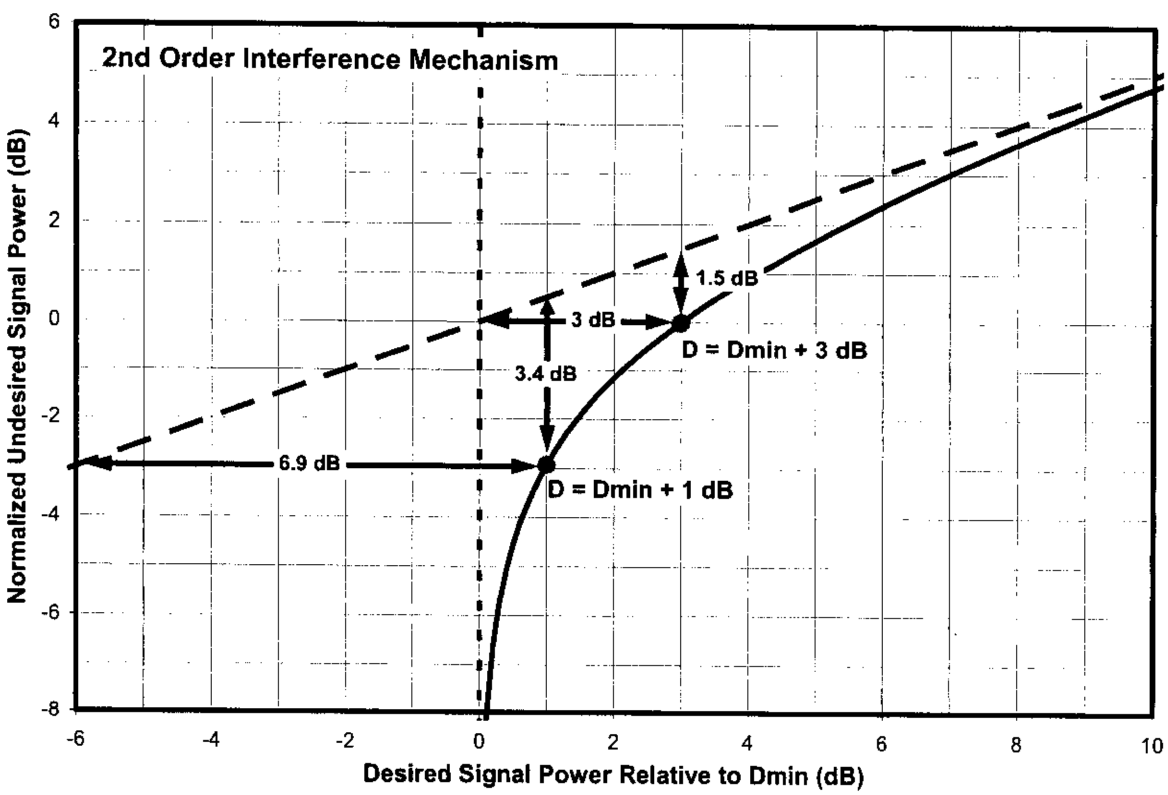

Figure 8-2. Deviation of Log-U Versus Log-D From Straight Line For 2nd-Order Interference

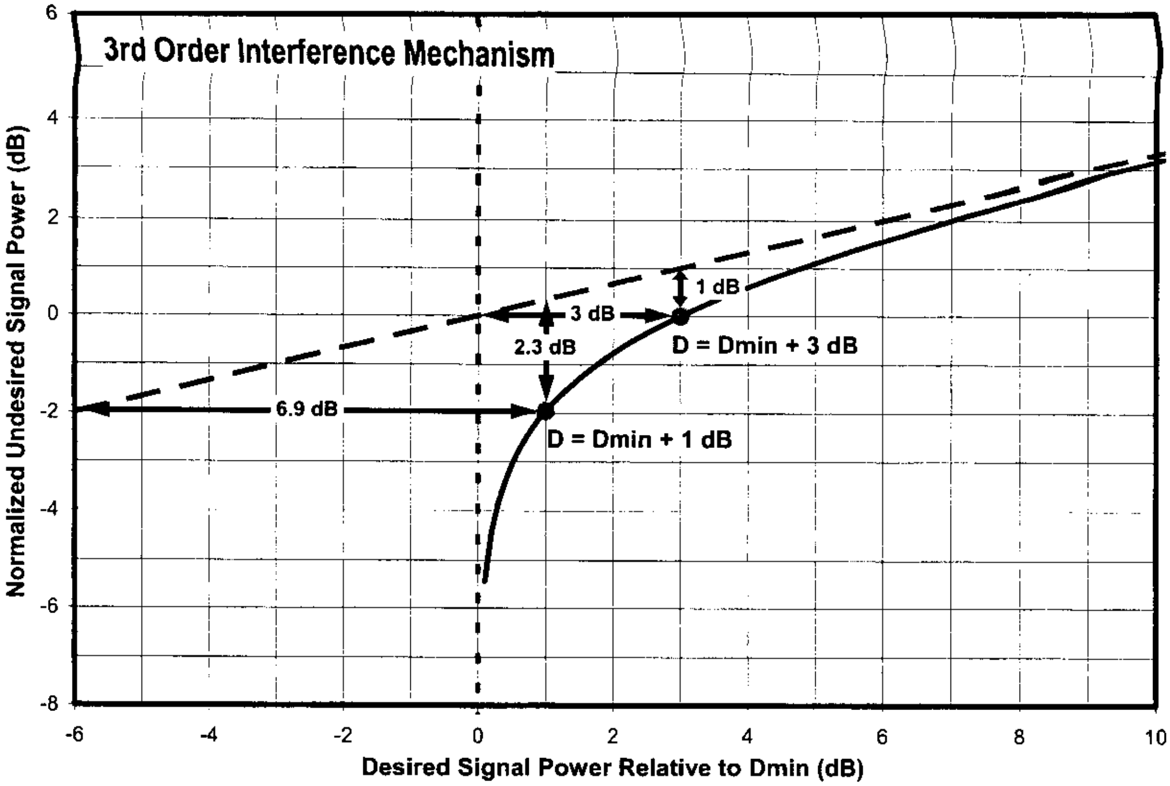

Figure 8-3. Deviation of Log-U Versus Log-D From Straight Line For 3[rd]-Order Interference

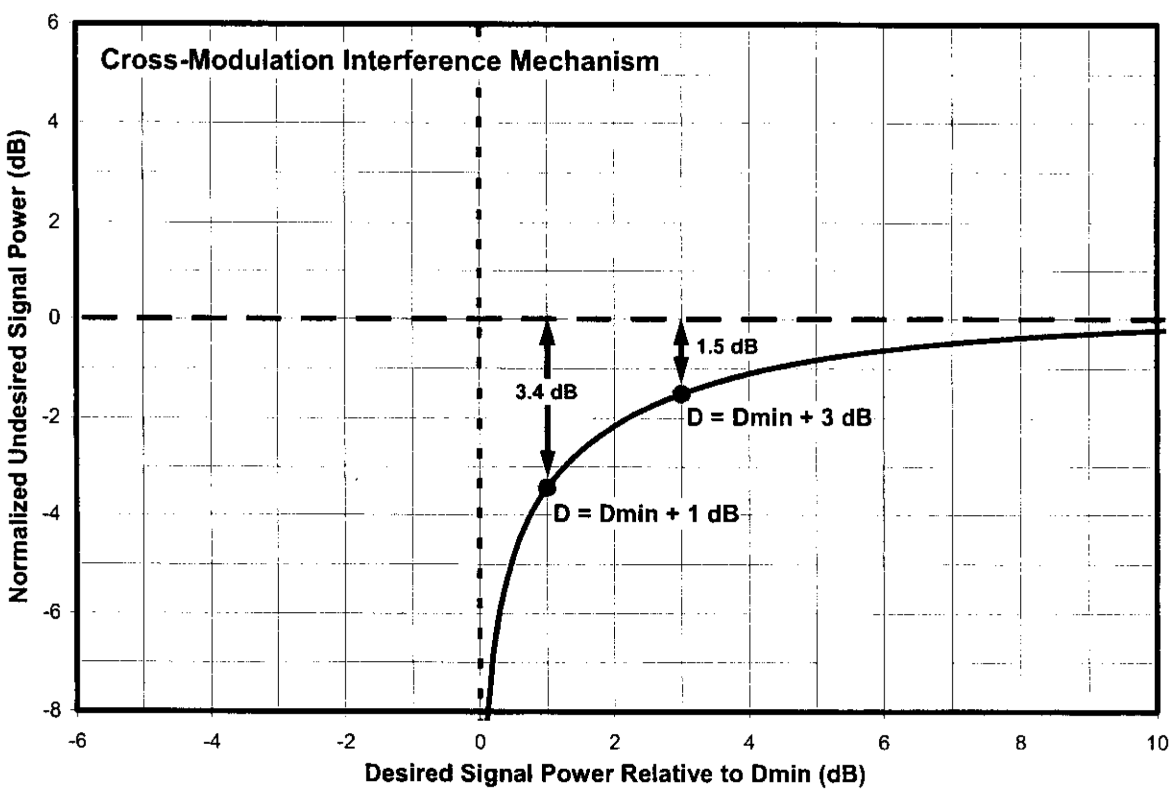

Figure 8-4. Deviation of Log-U Versus Log-D From Straight Line For Cross-Modulation

CHAPTER 9
THIRD-ORDER INTERMODULATION WITH PAIRED EQUAL-POWER INTERFERERS

Rhodes and Sgrignoli have raised the issue of ***third-order intermodulation (IM3)*** distortion occurring within a TV receiver between pairs of undesired input signals as a potentially significant interference mechanism for DTV reception.[*] [†] [‡] This chapter presents the results of interference rejection measurements performed using pairs of undesired signals spaced so as to place IM3 products into the desired channel. Thus, signal pairs were placed on channels N+K and N+2K, where K is a positive or negative integer. For this chapter the two undesired sources were maintained at equal power levels. Additional test results with paired signals are contained in Chapters 10 (unequal sources) and 11 (detailed measurements on one TV).

In all tests, the undesired signal placed farthest from the desired channel (*i.e.*, at N+2K) was a white Gaussian noise signal bandlimited to match the 3-dB width of an 8-VSB signal. For tests with the desired channel N = 51, the closer undesired signal (at N+K) to the desired channel N was an 8-VSB signal. For tests with the desired channel N = 30, the closer undesired signal was 8-VSB only if it was on a first-adjacent channel (N-1 or N+1); otherwise, the bandlimited Gaussian noise signal was used as the closer undesired signal source. The reason for the use of bandlimited Gaussian noise instead of 8-VSB was that, throughout most of the test period, only one 8-VSB source was available and it was needed as a desired signal source. Tests involving first adjacent channels were postponed until the procurement of another 8-VSB generator because the edge-of-band rolloff of the Gaussian source was not sufficient to support rejection tests on first adjacent channels.

Table 9-1 summarizes the test parameters. Only the test results from the first three rows of the chart are presented in this chapter. The fourth row describes tests at unequal undesired signal levels, which are presented in Chapter 10. The last row of the table identifies very detailed tests of the variation of D/U with desired signal level, which are presented in Chapter 11.

The purpose of these tests was to determine the extent to which pairs of undesired signals create an interference effect—through IM3 occurring within a TV receiver—that exceeds the effects of the individual signals.

SPECTRA OF THIRD-ORDER INTERMODULATION DISTORTION

IM3 creates signal components at frequencies that were not present in the input spectrum, but are in the same general frequency range as the input signals. The IM3 of interest in this chapter is created within the tuners of consumer DTV receivers. Since test points are not available within consumer receivers to show the actual signal effects that occur, spectra of IM3 components created by a laboratory instrumentation amplifier were measured to illustrate the concepts.[§]

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[*] Charles W. Rhodes, "Interference Between Television Signals due to Intermodulation in Receiver Front-Ends", IEEE Transactions On Broadcasting, Vol. 51, No. 1, March 2005, p.31-37.

[†] Charles W. Rhodes, and Gary J. Sgrignoli, "Interference Mitigation for Improved DTV Reception", IEEE Transactions on Consumer Electronics, Vol. 51, No. 2, May 2005, p. 463-470.

[‡] Charles W. Rhodes, "DTV interference could be mitigated by receivers," TV Technology Magazine, vol. 22, no. 17, p.21-23, Aug. 18, 2004.

[§] An HP8447E amplifier rated for 0.1 watts (20 dBm) output served as the IM3 producer. For the first illustration it was driven with a signal sufficient to create an output level of 8.1 dBm on each of one or two TV channels.

Table 9-1. Parameters for Paired-Interferer Tests (N+K/N+2K)

Chapter	Desired Channel N	Desired Signal Power	K	Undesired Signal at N+K	Undesired Signal at N+2K	Relative Power of U_{N+K} and U_{N+2K}	Number of DTV Receivers Tested
9	30	-68 dBm, -53 dBm, -28 dBm	1, -1	8-VSB	WGN[1]	Equal	8
9	30	-68 dBm, -53 dBm	2 through 5 and -2 through -5	WGN[1]	WGN[1]	Equal	8
9	51	-68 dBm, -53 dBm, -28 dBm	1 through 8	8-VSB	WGN[1]	Equal	7[2]
10	30	D_{MIN}+3 dB, -68 dBm, -53 dBm	2 or 3	WGN[1]	WGN[1]	Variable	2
11	51	D_{MIN}+1 dB, D_{MIN}+3 dB, -78 to -8 dBm in 5-dB steps	1 through 4	8-VSB	WGN[1]	Equal	1

Notes:
[1] WGN = white Gaussian noise signal bandlimited to match the 3-dB width of an 8-VSB signal.
[2] For one of the seven TVs tested at channel 51, the complete set of measurements was performed only for D = -68 dBm; for the other two levels, only N+1/N+2 tests were performed.

Figure 9-1(a) shows the spectrum of an 8-VSB signal on channel 34 after passing through the amplifier at a level 12 dB below the maximum rated output power of the amplifier. The "shoulders" that can be seen emerging from the sides of the 8-VSB spectrum about 33-dB below the main signal spectrum level are IM3 products. It can be seen that they extend through most of the width of each adjacent channel (channels 33 and 35), but not beyond. Thus, IM3 generated with a DTV tuner in response to an undesired signal on a single TV channel could influence reception of a desired signal on a *first-adjacent* channel. Put another way, if the TV is tuned to channel N, its reception there could be adversely impacted by IM3 caused by an undesired signal on channel N-1 or on channel N+1.

Figure 9-1(b) shows the effect of adding a signal of equal power on a second channel—in this case channel 38. The addition of the second signal causes the shoulders around the first signal to increase. A similar pair of shoulders is also created around the second signal. The spectral shoulders occupy channels 33, 35, 37, and 39—the channels adjacent to each of the input signals. In addition to the shoulders around each input signal, the presence of the second signal causes two other bumps in the spectrum to occur. One is centered on channel 30 and the other on channel 42, but they also spill over into the channels adjacent to those two channels. Thus, intermodulation products can now be found in channels 29, 30, 31, 33, 35, 37, 39, 41, 42, and 43.

If one imagines that a TV is attempting to receive a signal on channel 30 in the presence of the two undesired signals creating (within the TV tuner) intermodulation distortion shown in Figure 9-1(b), we would have the case of interference to channel N from an undesired signal pair, N+4/N+8. This is one of the cases examined in this chapter, as is the case of N-4/N-8, which would occur if the receiver were tuned to channel 42. (In test results shown in this chapter, the TV was always tuned to either channel 30 or channel 51, and the undesired signal channels were shifted appropriately.)

Figure 9-2(a) shows the effect of changing the amplitudes of both signals by 5 dB. The IM3 products change by 15 dB, as is expected since this is a third order process. From this we can conclude that if the undesired signal levels should rise, the interference effects created within the TV will rise even faster—at three times the rate of the rise in input signal level.

If only one of the two signals changes in amplitude, the results are somewhat more complex. Figure 9-2(b) shows the effect of a 5-dB change in amplitude of the signal at channel 34, while the one at channel 38 remains constant. The result is a 10-dB change in the amplitude of the IM3 bump closest the changed signal (*i.e.*, the bump at channel 30) and a 5-dB change in amplitude of the IM3 bump closest to the unchanged signal (*i.e.*, the bump at channel 42).

The tests in this chapter are configured so that undesired signals are placed on channels N+K and N+2K and the TV is tuned to channel N. Thus, channel N is centered on one of the outer spectral bumps. Figure 9-2(b) confirms the prediction shown in Chapter 8 that the interference power created at channel N is proportional to $U_{N+K}^2 U_{N+2K}$, where U_{N+K} and U_{N+2K} represent the respective power levels of the undesired signals. Thus, the interference created at channel N is a second order function of U_{N+K} and a linear function of U_{N+2K}.

CHANNEL-30 RESULTS AT THREE DESIRED SIGNAL LEVELS

"Weak" Desired Signal (D = -68 dBm)

Figure 9-3 shows measured D/U ratios at TOV for eight DTV receivers for pairs of equal-level undesired signals on channel pairs N+K/N+2K for K = -5, -4, -3, -2, -1, 1, 2, 3, 4, and 5 and a desired signal power of -68 dBm. The measurements were made with the TVs tuned to channel 30 as the desired channel N. The desired signal power was set to -68 dBm. In computing the D/U ratio, U was taken as the power of each signal in the signal pair rather than the combined power of the two signals; thus,

$$U = U_{N+K} = U_{N+2K}$$

The shaded area at the bottom of the plot represents the measurement limitations imposed by the test setup—as described in Chapter 4. None of these measurements were limited by the measurement system.

Though the ATSC A/74 has no recommended performance limits related to interference by a pair of signals, the red dashed curve labeled "A/74 Max of Pair" is provided as a reference based on single-channel ATSC interference rejection guidelines. For each point, N+K/N+2K, the value is equal to the higher (least restrictive) of the ATSC-recommended DTV-into-DTV interference rejection thresholds for single-channel DTV interferers. All of the TVs exhibited higher D/U ratios (poorer performance) at most points than is indicated by this A/74-based curve.

Figure 9-4 summarizes the measurements that were shown in Figure 9-3. The solid curve shows the median performance of the eight receivers. Error bars show the best and worst performance among the receivers at each channel offset. A dashed curve shows the performance of the second worst performing receiver at each channel offset.

Since the IF filter in a receiver is expected to greatly reduce signal levels available for creation of intermodulation products *after* the filter, one would expect that intermodulation between pairs of out-of-channel interferers would occur prior to the IF filter—probably in the mixer. Prior to the mixer, a typical single-conversion TV receiver would include a "tracking filter" that passes the desired channel but provides a gradually increasing attenuation to signals in other channels based on separation from the desired channel. The filter is expected to provide substantial attenuation at N+14 and N+15 in order to reduce the mixer image response. One would expect that such a tracking filter—if placed before the point of nonlinearity that created the intermodulation products—would cause interference effects of a

N+K/N+2K signal pair to diminish as |K| increases. Such a trend is evident in some, but not all of the *receivers, based on the measured data, which extends to |K| = 5.*

"Moderate" Desired Signal (D = -53 dBm)

Figure 9-5 shows D/U-ratio measurements at TOV for the same eight receivers at a higher desired signal level of -53 dBm. Figure 9-6 shows the median and range of the measurements, as well as the second worst performance among the eight receivers.

The expected rolloff with increasing |K| is even less evident than in the signal measurements that were made with a desired signal power of -68 dBm. In some cases, the influence of AGC operation on the N+1/N+2 and N-1/N-2 data may be partly responsible for the lack of increase at low absolute values of K. This topic is discussed more in Chapter 11.

"Strong" Desired Signal (D = -28 dBm)

Figure 9-7 shows the D/U measurements for a desired signal level of -28 dBm. At this signal level, the measurements were performed for only two channel pairs—N-1/N-2 and N+1/N+2. The maximum signal levels that could be generated by the test setup (about -7 dBm for each channel for adjacent-channel tests) were not high enough to create picture errors for most of the receivers. As a result, threshold measurements were possible on only three of the receivers for N-1/N-2 and only two of the receivers for N+1/N+2. The other measured points are shown at the measurement-limit line.

Figure 9-8 presents information regarding the best, median, second worst, and worst performance for each of the two channel pairs measured. Since there were only two points per curve, the data is presented in tabular form. The table shows the threshold values for the worst and second worst performers. The median and best performing values are shown only as "< [value]" because most of the data points were beyond the measurement limit of the test setup.

Combined Results With Single-Channel Reference Values

The plots shown in the previous three subsections provide no indication of whether the DTV picture errors are caused by IM3 interactions between the pair of undesired signals or whether they are caused by each signal independently.

To determine whether IM3 is the cause, it would be useful to show the interference thresholds for the individual undesired signals as well. Thus, we could plot the interference threshold for N+K/N+2K as well as the interference threshold for N+K alone and that for N+2K alone. An even better reference would be one that combined the effects of N+K interference and N+2K interference under the assumption that the interference mechanisms are independent and not the result of intermodulation. We attempt to take the latter approach—partly to reduce the number of curves that must be plotted so that results can be combined into a manageable number of graphs for this report.

The approach taken is to recognize that the observed interference phenomena are the result of mechanisms at work within the TV that convert out-of-channel undesired signals into co-channel interference at some point within the TV. The desired signal at threshold is then—in essence—a measure of the power level of that internal co-channel interference level, since the desired signal at threshold is expected to be about 15 dB above the co-channel interference. This concept was discussed in Chapter 8.

We will define D_{N+K} as the desired signal at threshold resulting from interferer U_{N+K}, and D_{N+2K} as the desired signal at threshold resulting from interferer U_{N+2K}. If we were to take measurements of D_{N+K} and D_{N+2K} at equal *undesired* signal levels ($U_{N+K}=U_{N+2K}=U$), then $D_{N+K} + D_{N+2K}$ would be the expected desired signal level threshold if both undesired signals were applied simultaneously ***and*** there were no interaction between them. (Summing D_{N+K} and D_{N+2K} is equivalent to summing the co-channel interference powers created within the receiver from each of the two undesired signals individually.) If the undesired signal powers are equal, this is equivalent to summing the D/U ratios:

$(D/U)|_{N+K/N+2K} = (D_{N+K}+D_{N+2K})/U = (D/U)|_{N+K} + (D/U)|_{N+2K}$, ***if there is no interaction between the two undesired signals.***

This provides a reference point for determining whether the paired-signal D/U is caused by the combined individual effects of the two undesired signals or a by nonlinear interaction between them (*i.e.*, IM3). Summing the D/U ratios to provide this reference point is strictly valid only if the measurements were performed at equal *undesired* signal levels (and if the AGC state of the tuner is the same for each measurement). Our measurements were performed with equal D values rather than equal U values; however, it would still be valid to apply this technique if D/U for the individual interferers were constant with variations in D. This is true of some cases but not for others. Even when it is not true, very little error is made in summing the D/U ratios if the interference effect (D/U ratio) for one interferer is much higher for the other, since, in that case the sum is approximately equal the D/U of the dominant interferer.

Based on the above we will plot the summed D/U ratio of the individual interferers along with the measured D/U ratio for the pair of interferers to provide an indication of whether IM3 effects are at work. (Note that the summing is performed on the direct power ratios, not on their values in decibels.)

Figures 9-9 through 9-16 show the measured D/U ratios for the paired interferers along with the summed D/U ratios for the corresponding individual interferers. Each graph presents the measurements for one DTV receiver. The two solid lines on each graph show the paired-signal D/U ratios measured at desired signal levels of -68 dBm and -53 dBm. The dashed lines show the summed D/U's for those signal levels. Note that if one or both of the individual D/U's was beyond the measurement limit of the test setup, then the sum was computed using the measurement limit; this fact may cause a summed D/U to exceed the paired-signal D/U if one element of the sum was at the measurement limit and the other was near the limit.

Where the solid lines are closely matched by the dashed summed-D/U lines, the interference effect of the pair of equal-powered undesired signals is primarily due to one of the individual signals—or to the combined effect of both—rather than to an IM3 interaction between the two interferers. Where a solid line is significantly higher than a dashed line, there is a significant IM3 effect from the pair of signals.

Notably, most of the receivers exhibit very little evidence of IM3 interaction from the N-1/N-2 and N+1/N+2 pairs. For a desired signal level of -68 dBm, the paired-signal D/U's exceed the summed signal D/U's by no more than 1.2 dB (and in most cases less than 0.5 dB) with one exception. For receiver G4 the difference is 4 dB at N-1/N-2. This indicates that, for equal-power paired undesired signals, any IM3 effects resulting from a signal pair on the first-adjacent channels (N-1/N-2 and N+1/N+2) of most receivers are insignificant relative to the interference sensitivities associated with the individual channels, at least for a desired signal power of -68 dBm. The one exception to this—one case out of 16 (8 receivers, upper and lower channel pairs)—yields a 4-dB increase in susceptibility as a result of IM3. At a desired signal power of -53 dBm, three of the 16 combinations exhibit an IM3 effect that is about 2 dB above the summed D/U's and one exceeds the summed D/U's by 3.6 dB.

Even at N-2/N-4 and N+2/N+4 about half of the receivers exhibit little or no evidence of an IM3 effect for paired equal-power undesired signals. Among the other half, some exhibit very pronounced IM3 effects up to 11 dB above the summed D/U's.

At larger channel spacings, there is evidence of IM3 from the signal pairs significantly exceeding the interference effect of the individual interferers—by amounts up to at least 17 dB. (In cases where summed D/U's are computed from measurements that were at the limit of the measurement setup, the actual summed D/U's are lower than those shown, so the true amount of the excess is greater than that shown.)

An unexpected and seemingly impossible behavior can be seen for receiver D3 (Figure 9-10) at N-2/N-4 for a desired signal level D = -53 dBm. The D/U for the pair of interferers operating together is actually *significantly lower than the summed D/U's for the individual interferers. Examination of the single-*channel data shows that the receiver is far more sensitive to interference at N-4 (D/U = -32.3) than at N-2 (D/U = -49.0 dB); however, the D/U ratio for the pair of signals (with U referring to the undesired power on *each* of the two channels) is only -38.8 dB, 6.5 dB less than the D/U for N-4 alone. Put another way, an undesired signal level of -20.8 dBm on channel N-4 causes picture errors on the TV, but if a *second* undesired signal is placed on channel N-2, the TV can tolerate a higher interference level of -14.3 dBm on each of the channels simultaneously!

This result is highly counter-intuitive until one examines detailed test results for that TV—presented in the Chapter 11. Though those measurements are limited to cases with interferers on higher channel numbers than the desired signal (N+K/N+2K with positive values of K), the data suggests that the presence of an undesired signal on channel N+2 any higher than approximately -35 dBm causes the DTV receiver's AGC to reduce the RF gain, whereas an undesired signal at N+4 causes no such gain reduction (or, if it does, the reduction occurs at a higher signal level). In the case described above, the TV is very susceptible to interference from an undesired signal placed at N-4, probably due to a nonlinearity in the tuner; but, adding in an undesired signal at N-2 probably causes the AGC to reduce the RF gain of the tuner (as was the case at N+2), which reduces the signal levels at the point of the nonlinearity. A theoretical basis for understanding the effect of AGC on interference phenomena was presented in Chapter 8 (with more details in Appendix B). More discussion about the effect of AGC will be presented in Chapter 11 on the basis of detailed measurement data for Receiver D3.

Table 9-2 shows statistics for the difference (in dB) between the paired-signal D/U's and the summed D/U's for the eight TV receivers that were tested. Looking across all of the data, we see that a pair of appropriately-spaced equal-power undesired signals can create an intermodulation effect that enhances the interference potential of the signals. The combined signals can cause TV picture degradation (or loss) at signal levels at least as much as 17 dB lower than the levels that would be required to cause picture degradation based on the combined individual effects of each signal, *i.e.*, without intermodulation between the pair. (The actual difference may have been much larger. See the note in table.) At the other extreme, paired signals applied to some TV receivers on some N+K/N+2K channel pairs cause no increase in interference effect above the summed effects of the individual signals, and in one case (discussed in the preceding paragraph), AGC action causes the paired signal combination to have less of an interference effect than that of one of the individual signals.

CHANNEL-51 RESULTS AT THREE DESIRED SIGNAL LEVELS

In this section we present the results of paired-signal rejection measurements made with the TVs tuned to channel 51 as the desired channel N. The two undesired signals were placed on N+K and N+2K for K = 1 through 8. The reason for limiting these tests to positive values of K is that the focus was on potential for interference to upper UHF channels from other radio services that are expected to operate in channels 52 through 69 after completion of the DTV transition.

For these tests, the undesired signal on channel N+K was an 8-VSB DTV signal. The undesired signal on channel N+2K was a white Gaussian noise source bandlimited to match the 3-dB width of an 8-VSB DTV signal.

Table 9-2. Statistics of Paired-Signal D/U's Relative to Summed D/U's for 8 Receivers on Channel 30

Undesired Channel Pair	Excess of Paired-Signal D/U Above Summed D/U's (dB) D = -68 dBm Min	Mean	Median	Max	D = -53 dBm Min	Lower Bound on Mean[1]	Lower Bound on Median[1]	Lower Bound on Max[1]
N-5/N-10	1.8	9.8	9.8	15.7	3.4	*11.7*	*11.7*	*16.9*
N-4/N-8	0.4	5.7	5.1	12.2	3.4	*9.5*	*9.8*	*16.3*
N-3/N-6	-1.2	5.2	3.1	15.1	-0.2	5.9	6.4	11.3
N-2/N-4	-1.9	-0.2	-0.6	3.0	-6.6	0.5	0.2	5.6
N-1/N-2	-0.3	0.7	0.2	4.0	-0.3	0.7	0.1	3.6
N+1/N+2	-1.5	0.0	0.3	0.6	-1.3	0.6	0.5	2.3
N+2/N+4	-1.5	2.7	0.1	11.3	-1.2	4.0	3.9	11.4
N+3/N+6	-0.2	7.2	6.8	14.1	2.1	*9.8*	*9.9*	*14.7*
N+4/N+8	1.5	8.2	7.0	16.4	0.7	*8.7*	*8.9*	*13.8*
N+5/N+10	0.0	7.9	9.1	12.8	-0.3	*7.1*	*7.3*	*13.7*
	-1.9	**4.7**	**4.1**	**16.4**	**-6.6**	**5.9**	**6.8**	**16.9**

Note

[1] For D = -53 dBm, the actual means, medians, and maxima for channels N+3/N+6 and beyond on the positive side and N-4/N-8 and beyond on the negative side are underestimated because most of the individual measurements on which the summed D/U's are based were for measurement conditions in which TOV for the receivers was not reached due to limitations on maximum signal that the test setup could generate; consequently, the values shown in red italics should be viewed as lower bounds on the actual values.

"Weak" Desired Signal (D = -68 dBm)

Figure 9-17 shows measured values of D/U ratios at TOV for seven DTV receivers for pairs of equal-level undesired signals with the desired signal power was set to -68 dBm. The seven receivers are a subset of the eight that were tested for the previous major section of this chapter. The reader is referred to the channel-30 section of this chapter for more information on the plot format.

Figure 9-18 summarizes the measurements that were shown in Figure 9-17. The solid curve shows the median performance of the eight receivers. Error bars show the best and worst performance among the receivers at each channel offset. A dashed curve shows the performance of the second worst performing receiver at each channel offset.

For the most part the D/U ratios exhibit an expected drop (indicating less susceptibility to interference) as the channel spacing from the desired channel increases. There are some exceptions. The increase in D/U for receiver D3 as the undesired signal pair is moved from N+1/N+2 to N+2/N+4 is believed to be the result of an AGC gain reduction occurring when the undesired signal is placed on N+1. This will be discussed further in Chapter 11. The peak exhibited by some TVs at N+7/N+14 is the result of single-channel effects at N+7 (the local oscillator frequency) or N+14 (mixer image frequency).

"Moderate" Desired Signal (D = -53 dBm)

Figure 9-19 shows D/U-ratio measurements at TOV for the same seven receivers at a higher desired signal level of -53 dBm. We note that only one measurement was performed on receiver N1 at this desired signal level—at N+1/N+2.* Figure 9-20 shows the median and range of the measurements, as well as the second worst performance among the receivers; except for N+1/N+2, the data are for only six of the receivers.

The expected rolloff with increasing |K| is less evident than in the "weak"-signal measurements. In some cases, the influence of AGC operation on the N+1/N+2 and N-1/N-2 data may be partly responsible.

"Strong" Desired Signal (D = -28 dBm)

Figure 9-21 and 9-22 show corresponding plots of D/U measurements of seven receivers for a desired signal level of -28 dBm. As in the case of -53 dBm, one of the receivers was measured only at N+1/N+2. Most of the D/U ratios fall outside the measurement range of the test setup.

Combined Results With Single-Channel Reference Values

Figures 9-23 through 9-29 show the measured D/U ratios for the paired interferers along with the summed D/U ratios for the corresponding individual interferers. Each graph presents the measurements for one DTV receiver. The solid colored lines on each graph show the paired-signal D/U ratios measured at desired signal levels of -68 dBm, -53 dBm, and -28 dBm.

The dashed lines on each graph show the summed D/U's for each of the three desired signal levels. The summed D/U's represent the summed interference effects of the two undesired signals in the absence of any intermodulation products generated by nonlinear interactions of one signal with the other. Note that if one or both of the individual D/U's was beyond the measurement limit of the test setup, then the sum was computed using the measurement limit. This occurred for many of the summed D/U values for D = -68 dBm and most of those for D = -53 dBm and D = -28 dBm. Where it occurred, the actual TOV levels for the individual undesired signals are unknown, and the actual differences between the paired-signal D/U's and the summed D/U's are greater than those shown in the charts. Because of the number of data points affected by this limitation, the channel-51 data were not tabulated as the channel-30 data were. We also note that the use of measurement limit values sometimes caused a summed D/U value on the plots to artificially exceed the paired-signal D/U when one element of the sum was at the measurement limit and the other was near the limit—a condition that occurred for most of the measurements for D = -28 dBm.

Where the solid lines are closely matched by the dashed "summed D/U" lines, the interference effect of the pair of interferers is primarily due to one of the individual interferers—or the combined effect of both—rather than an IM3 interaction between the two interferers. Where the solid lines significantly exceed the dashed lines, there is a significant IM3 effect from the pair of signals.

ESTIMATING 3RD ORDER INTERCEPT POINT (IP3)

The measurements presented in this chapter can be used to determine the DTV receiver's third-order intercept point (IP3)—a property that quantifies the nonlinearity of the receiver and allows computation of IM3 interference effects from undesired signal amplitudes that differ from the levels actually tested. Our use of the term IP3 here, while similar to its traditional use in characterizing amplifiers, differs from the traditionally defined IP3 in two ways:

- The measurements here were made with broadband, noise or noise-like signals rather than with the CW (continuous wave) sinusoids usually used for IP3 measurements; since the process is a third-order one, one would expect the effective interference power to be related to the sixth-order moments of the input signals; those moments are expected to be higher for the noise-like waveforms than for a sinusoid of the same input power;

* This test series was terminated by equipment failure, followed by a change in focus of the test program.

- As Figure 9-2 showed, the IM3 power in each side "bump" of the spectrum is split across three TV channels, of which only the center one (where most of the power is concentrated) is "measured" by the TV in our tests; thus, a portion of the IM3 power is excluded from the measurement.

There are three limitations on such IP3-based assessment of DTV interference:
(1) IP3 can be quantified from the paired-signal measurements only if the observed interference is primarily due to IM3 between the signal pair;
(2) While IP3 is usually treated as a constant for a given amplifier, it will, in fact, vary with AGC operation; and,
(3) IP3 computation depends on a knowledge of the signal-to-noise ratio necessary for the receiver to reach TOV because we are not measuring IM3 effects directly, but rather are inferring them from measurements of U and D at TOV.

Regarding the first limitation, we will compute IP3 only when the D/U ratio for the pair of signals exceeds the summed D/U ratios of the individual signals (plotted as reference curves in Figures 9-9 through 9-16 and 9-23 to 9-29) by at least 4 dB.

Regarding the second limitation, we will recognize that IP3 will be constant only when desired and undesired signal levels are low enough not to cause AGC gain reductions prior to the point of the nonlinearity that causes the IM3. We will attempt to use changes in measured IP3 to determine whether or not the AGC is active in the vicinity of a paired-signal measurement.

Regarding the third limitation, we could choose to substitute a value such as 33.9 (*i.e.*, 15.3 dB converted to a linear power ratio) for the required signal-to-noise ratio (SNR_R) since all of the receivers have required signal-to-noise ratios close to this value (according to measurements presented in the SHVERA Study*); however, that value was measured using white Gaussian noise as the interferer, and, strictly speaking, the SNR required to overcome IM3 interference may differ from that of white Gaussian noise due to differing spectral shape or perhaps statistical properties. Consequently, we choose to incorporate the SNR_R term into the quantity calculated to quantify the receiver's nonlinearity.

Thus, instead of computing IP3, we choose to compute the quantity, $IP3 / SNR_R^{1/2}$, which was shown in Chapter 8 to be related to desired and undesired signal powers at threshold for paired-signal IM3 interference. In linear power units, the quantity can be computed by

$$IP3 / SNR_R^{1/2} = (U^3 / D)^{1/2}$$

In decibel units, it is given by

$$(IP3 / SNR_R^{1/2})|_{dB} = 1.5\, U|_{dB} - 0.5\, D|_{dB}$$

The values of $IP3 / SNR_R^{1/2}$ computed here will be applied to the case of unequal undesired signal levels in the next chapter.

Channel 30

Table 9-3 and Figures 9-30 and 9-31 present computed values of $IP3 / SNR_R^{1/2}$ (in dB) based on the channel-30 measurements of rejection ratios for paired signals. Values were computed only when the paired-signal D/U ratio exceeded the summed single-signal D/U ratios by at least 4 dB, as stated above. The blank cells represent measurements that did not meet this condition. See the note at the bottom of the table for conversion to IP3.

* Martin, <SHVERA Study>, 2005, chapter 3.

Table 9-3. IP3/SNR$_R^{1/2}$ Based on Paired-Signal Rejection Measurements at Channel-30

		IP3 / SNR$_R^{1/2}$ (dB)									
	K→	**-5**	**-4**	**-3**	**-2**	**-1**	**1**	**2**	**3**	**4**	**5**
Receiver	**D (dBm)**	**N-5/ N-10**	**N-4/ N-8**	**N-3/ N-6**	**N-2/ N-4**	**N-1/ N-2**	**N+1/ N+2**	**N+2/ N+4**	**N+3/ N+6**	**N+4/ N+8**	**N+5/ N+10**
A3	-68								***0.7***	***3.9***	***6.8***
D3	-68	-5.5	-9.4	***-13.9***				***-24.7***	-17.1		
G4	-68	***-1.3***	***-0.1***	-3.4				***-10.4***	***-7.1***	***-4.8***	***-1.3***
I1	-68	***-12.2***								***5.2***	***3.7***
J1	-68	***-3.9***							***-6.4***	***-4.3***	***2.0***
M1	-68	***-5.4***	***-5.0***	***-5.5***				***-5.2***	***-6.1***	***0.6***	***5.1***
N1	-68	***6.7***								***7.6***	
O1	-68	***-5.2***	***-7.1***	-5.4						***8.2***	***7.7***
A3	-53	***5.4***	2.2	-2.8	0.5			-0.8	***-0.5***	***2.7***	***5.6***
D3	-53			***-14.9***				***-21.7***			
G4	-53	***1.8***	***-0.7***	7.6	5.7			-5.8	***-8.2***	***-1.7***	3.2
I1	-53	-4.3	0.4						6.0	***5.4***	***3.8***
J1	-53	***-1.4***	-3.3						***-3.1***	***-1.3***	***-1.5***
M1	-53	***-4.7***	***-4.3***	0.9				1.9	***-3.2***	***-2.5***	***4.7***
N1	-53	***1.5***	4.7	5.2					7.0	***6.8***	
O1	-53	***-3.9***	-1.6	12.4					9.3	***8.8***	***7.8***

Notes:

- *Outlines represent receivers and channel offsets subjected to further measurement in the next chapter.*
- *IP3 can be estimated by adding SNR$_R|_{dB}$/2 (nominally 15.3 / 2 = 7.6 dB) to the values of (IP3 / SNR$_R^{1/2}$)$|_{dB}$ shown.*

In the table, bold italics with shading indicates values that are believed to correspond to full gain operation of the receiver through the mixer (*i.e.*, no RF AGC operation); this judgment was made on the basis of the change in computed IP3 as desired signal level changed from -68 dBm to -53 dBm. (Note the lack of shading does not necessarily indicate that AGC *did* operate in a given region; rather, it may indicate that the measurements were insufficient to make a judgment.) If the AGC was *inactive* throughout the range, one would expect a constant IP3 value. If the AGC *operated* throughout the range to maintain constant signal levels at the point of nonlinearity, one would expect IP3 to increase by 15 dB (same change as D). The observed IP3 changes from D = -68 dBm to D = -53 dBm within the same receiver ranged from -5 to +18 dB. AGC was judged to have operated throughout the range if the IP3 change was greater than 10 dB; in that case, corresponding cells for both -68 dBm and -53 dBm are marked as having been influenced by AGC. Pairs with lower IP3 changes were judged to have had AGC operation through no more than part of the range, so the low end of the range (D = -68 dBm) was judged not to have been influenced by AGC. Where IP3 change was less than 3.5 dB, we judged that both ends of the range were free of AGC operation.

Measurable IM3 effects were not observed on the first-adjacent channel cases (N+1/N+2 and N-1/N-2) and many of the second-adjacent channel cases (N+2/N+4 and N-2/N-4). This is believed to be a result of two factors: (1) AGC-induced gain reductions in each receiver's front end reduced the amplitudes of IM3 effects for those channel offsets; and (2) those channel offsets exhibited higher single-channel interference effects that would have tended to mask the IM3 effects.

In Figure 9-30, which presents IP3 / $SNR_R^{1/2}$ values for D = -68 dBm, the expected increase in IP3 with increasing offset from channel N due to filtering in the receiver front end is clearly evident for most receivers on the right half of the graph where there are more data points. Such a tendency is seen at D = -53 dBm (Figure 9-31) for fewer receivers.

Channel 51

Table 9-4 and Figures 9-32 and 9-33 present computed values of IP3 / $SNR_R^{1/2}$ (in dB) based on the channel-51 measurements of rejection ratios for paired signals. As with the channel-30 measurements, values were computed only when the paired-signal D/U ratio exceeded the summed single-signal D/U ratios by at least 4 dB. The blank cells represent measurements that did not meet this condition. The reader is referred to the discussion in the previous section (for channel 30) for information regarding the shading in the table. See the note at the bottom of the table for conversion to IP3.

For D = -68 dBm (Figure 9-32) most receivers exhibit an increase in IP3 with increased spacing between the undesired channels and the desired channel. Such a trend is not clear for D = -53 dBm (Figure 9-33); in fact, receiver I1 exhibits a very flat IP3.

Table 9-4. IP3/$SNR_R^{1/2}$ Based on Paired-Signal Rejection Measurements at Channel-51

		IP3 / $SNR_R^{1/2}$ (dB)							
	K→	1	2	3	4	5	6	7	8
Receiver	D (dBm)	N+1/ N+2	N+2/ N+4	N+3/ N+6	N+4/ N+8	N+5/ N+10	N+6/ N+12	N+7 /N+14	N+8/ N+16
A3	-68			***-2.5***	***1.7***	***5.3***	8.8		
D3	-68		***-25.6***	-17.8					
I1	-68				***4.8***	***4.7***	***4.0***		***4.1***
J1	-68			***-3.6***	***-3.5***	***2.7***	***6.1***	7.9	9.2
M1	-68		***-3.4***	***-2.0***	***3.0***	8.2	13.4		
N1	-68			4.9	0.2	0.4	3.1		5.0
O1	-68					8.7	7.9		7.8
A3	-53		1.1	***-2.5***	***1.8***	***5.3***			
D3	-53		-18.7						
I1	-53			5.8	***5.4***	***4.8***	***4.6***	4.3	***5.3***
J1	-53			4.5	***-1.1***	***0.2***	***3.6***		
M1	-53		1.0	***0.2***	***2.8***				
N1	-53		NM	NM	NM	NM	NM	NM	NM
O1	-53								

Notes:

- ***Bold italics with shading*** *indicates probable operation at signal level low enough to avoid AGC operation; that assessment is based on the observed change in IP3 / $SNR_R^{1/2}$ as desired signal level changes from -68 dBm to -53 dBm. (See text for details.)*
- *NM (for receiver N1) indicates that no measurements of paired-signal D/U ratio were made due to equipment failure. The lack of measurements for receiver N1 at D = -53 dBm precluded the opportunity to estimate AGC operation; consequently, none of the N1 measurements at D = -68 dBm could be judged to be free of AGC gain changes.*
- *IP3 can be estimated by adding $SNR_R|_{dB}/2$ (nominally 15.3 / 2 = 7.6 dB) to the values of $(IP3 / SNR_R^{1/2})|_{dB}$ shown.*

Comparison of Channels 30 and 51

Figure 9-34 combines the IP3 / $SNR_R^{1/2}$ data measured on channels 30 and 51 for a desired signal power of -68 dBm. The measurements include up to four channel pairs in common. For most of the TV receivers, there is a close match between the measurements in the overlap region.

SUMMARY DATA

The IP3 data tables are incompletely filled because of our restriction that we computed the IP3 parameter only when the paired-signal D/U ratio exceeded the summed single-signal D/U ratios by at least 4 dB. Thus, data could be missing because the IM3 effects are small, because the interference effects of the corresponding single-channel undesired signals are high, or because some single-channel measurements on which the summed D/U's are based are at the measurement limit of the test setup. This makes it harder (and in many cases, impossible) to determine worst-case, second-worst, and median values from the existing measurements without introducing biases.

We carefully examined both the paired-signal D/U measurements and the corresponding single-channel D/U measurements including combinations in which IP3 is not reported due to the paired-signal D/U ratio not meeting the threshold requirement described above. This evaluation was used to determine, where possible, the values for median, second-worst, and worst (lowest) IP3 values among the channel pairs. The results are shown in Table 9-5 for both channels 30 and 51. The final three columns combine the data from the two desired channels—by averaging when measurements exist on both channels—to provide a larger view of the IP3 variation with channel-pair spacing.

Table 9-5. IP3/$SNR_R^{1/2}$ Statistics

	IP3 / $SNR_R^{1/2}$ (dB)								
	Channel 30			Channel 51			Combined		
	Worst	2nd Worst	Median	Worst	2nd Worst	Median	Worst	2nd Worst	Median
N-5/N-10	-12.2	-5.5	-4.5				**-12.2**	**-5.5**	**-4.5**
N-4/N-8	-9.4	-7.1	-5.0				**-9.4**	**-7.1**	**-5.0**
N-3/N-6									
N-2/N-4									
N-1/N-2									
N+1/N+2									
N+2/N+4									
N+3/N+6	-17.1	-7.1	-2.7	-17.8	-3.6	-2.0	**-17.5**	**-5.3**	**-2.4**
N+4/N+8	-4.8	-4.3	2.2			1.7	**-4.8**	**-4.3**	**1.9**
N+5/N+10	-1.3	2.0	4.4	0.4	2.7	4.7	**-0.5**	**2.3**	**4.5**
N+6/N+12				3.1	4.0	6.1	**3.1**	**4.0**	**6.1**
N+7/N+14									
N+8/N+16				4.1	5.0	9.2	**4.1**	**5.0**	**9.2**

The results can be used to compute threshold values of undesired signal power U and D/U ratio when the two undesired signals have equal power:

$$U|_{dB} = (1/3)\,[2\,(IP3 / SNR_R^{1/2})|_{dB} + (D - D_{MIN})|_{dB}]$$

where $(D - D_{MIN})|_{dB}$ is computed by converting the desired power levels to linear power units (*e.g.*, mW), performing the subtraction, and then converting back to dB.